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A FAST-RUNNING, PHYSICS-BASED TOOL FOR EXPLOSIVES IN TUNNELS: MODEL VALIDATION

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ABSTRACT

An overview of the fast-running, physics-based model developed at Lawrence Livermore National Laboratory to provide rapid and accurate analysis when considering an explosive blast within a tunnel is presented, with focus on the verification and validation of the model. The performance of STUNTOOL, our 1-1/2 dimensional (1D) physics model, STUNTOOL, is compared to higher-fidelity ALE3D two-dimensional (2D) axisymmetric calculations and experimental results. For an explosive blast in a straight tunnel, STUNTOOL shows excellent agreement with experiment. For the case of an explosion in a tunnel where the blast wave encounters a sudden decrease in cross-section, it is found that the numerical results from both codes are in good agreement until the interface at the change in cross section is encountered. Thereafter, however, the peak pressures derived with the codes are found to be significantly higher than experimental results; although the agreement between the 2D result and the experiment improves with increasing distance down the tunnel. Peak pressure and impulse per unit area obtained downstream of the interface with the STUNTOOL 1D analysis are found to be substantially higher than with either the experiment or the 2D values. This is a result of the time delay for the shock reflecting off the (vertical) rigid wall between the inner and outer tunnel radii to interact with the (supersonic) core flow into the decreased cross section. In the 1D case, the reflected and transmitted shocks are formed instantaneously across the entire cross section resulting in higher pressure and increased shock speed downstream of the interface. The implications of this effect for modeling tunnel structures are discussed.

INTRODUCTION

High performance computing together with hydrodynamic and structural analysis tools such as the ALE3D, DYNA3D and CTH codes [1, 2, 3] can be used to predict the response of structures to shock loads and assist in the implementation of vulnerability corrective measures [4, 5, 6]. Such codes are also useful for validation of structural response as they can capture the full time varying three-dimensional response of structures [7, 8]. As it is difficult to use these tools to conduct a timely assessment of a large range of threats and threat locations due to the computational resources required, there is a need for more expedient tools that can be used to rapidly evaluate the effects associated with explosive blasts from various threat sizes, threat locations, and system states. A challenge for such 'fast-running' tools is validation to meaningful experimental data.

We have developed a fast-running tool that can be used to estimate the effects of explosive blasts in tunnels. One component utilizes a physics-based approach for predicting shock propagation in tunnels that runs in seconds to minutes on a single processor. This capability allows users to determine the loading environments associated with the range of credible threat configurations and locations. The effects on blast loading of varying the tunnel system can also be rapidly explored. The second component of our tool is a statistical treatment for predicting and bounding close-in structural response, specifically breach vs. no breach conditions, at varying threat standoff distance using previously executed high fidelity analysis. The results are compiled into breach curves that allow the user to quickly determine if damage to the tunnel severe enough to breach the wall is likely for a range of threat conditions. Description of the structural and statistical analyses employed to construct the breach curves can be found in Glascoe et al., 2012 [6] and Lennox and Glascoe, 2011 [9].

Direct simulation of blast propagation in tunnels is a formidable task due to a combination of factors. First, the flow in tunnels is dominated by boundary layer effects; capturing these effects requires fine radial resolution. Second, tunnels tend to have high length over diameter ratios, resulting in an extensive computational domain relative to tunnel diameter. The coupling of these two features makes direct three-dimensional simulation of flow in long tunnels prohibitively expensive. Even two-dimensional (2D) simulations of extensive tunnel lengths can become too expensive when considering multiparameteric study. The sphere and tunnel code (STUN) used in our tool (STUNTOOL) employs a simpler algorithm that captures the essential physics of blasts in tunnels [10], but runs in

minutes on standard personal computing hardware. STUN is based on an algorithm originally developed for the study of hypervelocity launchers and gas guns [11, 12].

The STUN code solves the 1D fluid flow equations of mass, momentum and energy. The effects of wall drag are accounted for in the momentum equation using a friction factor, f, which is a function of Reynolds number. With appropriate selection of f, this approach is applicable for both laminar flow (Stokes' law) and turbulent flows (Prandtl-Karman law of the wall) [13]. For simulation of an in-tunnel blast, STUN couples several 1D representations of the tunnel and blast into a higher dimensional representation. Specifically, the code solves a spherical flow problem for the detonation that is coupled to 1D axial flow through the tunnel segments. By varying the cross section of the tunnel along its length, it is possible to account for the effect of stations or platforms (larger cross section) and trains (restricted cross section) upon the blast wave. STUN can predict the effect of an arbitrary number of bends in the tunnel system and supports coupling to additional tunnel segments to simulate the effect of tunnel intersections on the shock wave. Including such details in a high-fidelity code makes the simulation inherently three-dimensional and far more expensive. In contrast, the cost of the corresponding STUN calculation is only minimally greater. STUN is ideally suited for rapidly providing pressure histories at a distance along a complex tunnel/station configuration. These results can be used to estimate, for example, down-tunnel blast effects on personnel or impulse loading of structural components.

This paper details continuing validation efforts for the Sphere and Tunnel (STUN) code, the fast-running physics-based code that makes up the first component of our tool. STUN has been validated previously for blast propagation through tunnels using several sets of experimental data with varying charge sizes and tunnel configurations, including the MARVEL nuclear driven shock tube experiment [10]. Here, STUNTOOL results are compared to experimental data from two small-scale high explosive experiments in pipes and results obtained with the LLNL ALE3D hydrocode.

MODEL VALIDATION: A SMOOTH, STRAIGHT PIPE

Lunderman and Ohrt [14] obtained blast pressure data from a series of small-scale high explosive experiments in a smooth, straight pipe section. We compare the performance of the STUNTOOL and ALE3D codes in modeling these experimental results [15]. In the experiment, a straight tunnel section was simulated with a 243mm inner diameter (D) steel pipe (10 inches Schedule 80 steel pipe). A final assembled pipe length of about 7.75 meters was formed from pipe sections connected with heavy bolted flanges. The tunnel inlet was constructed with steel plates to emulate the entrance to a real tunnel in a mountainside and the far end of the pipe was generally left open. Diaphragm-type air blast gages flush-mounted to the wall of the pipe were used to record blast pressure profiles. Spherical explosive charges were formed from hand-packed hemispheres of composition C-4 surrounding a detonator to approximate a center-detonated charge. The charge was suspended by the firing line of the detonator to the centerline of the pipe. A series of detonations were conducted with varying charge size and location. The numerical simulations mimic the experimental configuration with a 15.7g C-4 charge located four diameters ($4D$) from the inlet inside the pipe.

The dimensions of the tunnel and the charge properties were matched to the experimental set up with each of the two codes. The Jones-Wilkins-Lee (JWL) equation of state was used to model the energy released in detonation and the air properties were determined with a gamma law in both simulations. The corresponding ALE3D calculation was conducted in 2D, taking advantage of the axial symmetry and simple tunnel geometry to obtain high-fidelity computational results for additional comparison. The steel pipe was not modeled; the boundary at the inner diameter of the pipe was assumed to be rigid. Mesh refinement effects were investigated and found to be negligible at the resolutions considered, between 2.5 mm and 1.7 mm for the ALE3D simulation. Simulation details are given in Table 1.

Table 1: Simulation details for comparison to small scale smooth straight pipe experiment

Simulation:	1D STUNTOOL	2D ALE3D
Resolution	8.94mm	1.7mm
# of Elements	773	230,000
Wall time	< 1 min	96 hours

Number of Processors	1	24
Total Computational Time	< 1 min	2304 hours

Peak pressure and impulse results from each simulation and the experiment are shown in Figure 1. Both simulations match the experimental data well. Very close to the explosive source, the simulations under-predict the peak pressure measured in the experiment. The STUN calculation show slightly better agreement than ALE3D for pressure close to the explosive source, and agreement to experiment for both simulations improves for x/D locations greater than one. As the shock travels down the tunnel, it develops into normal shock propagation, and the agreement between the three results improves. ALE3D peak impulse is somewhat under-predicted. Full pressure and impulse profiles at 15.7 diameters down the tunnel from the detonation location are shown in Figure 2; the STUNTOOL profiles at this measurement position are virtually congruent with the experimental ones.
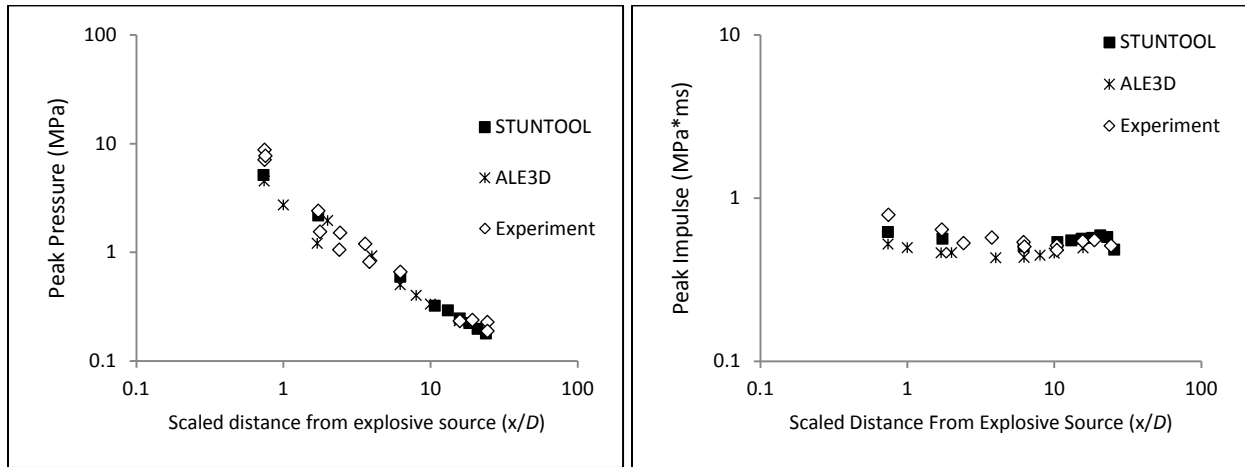

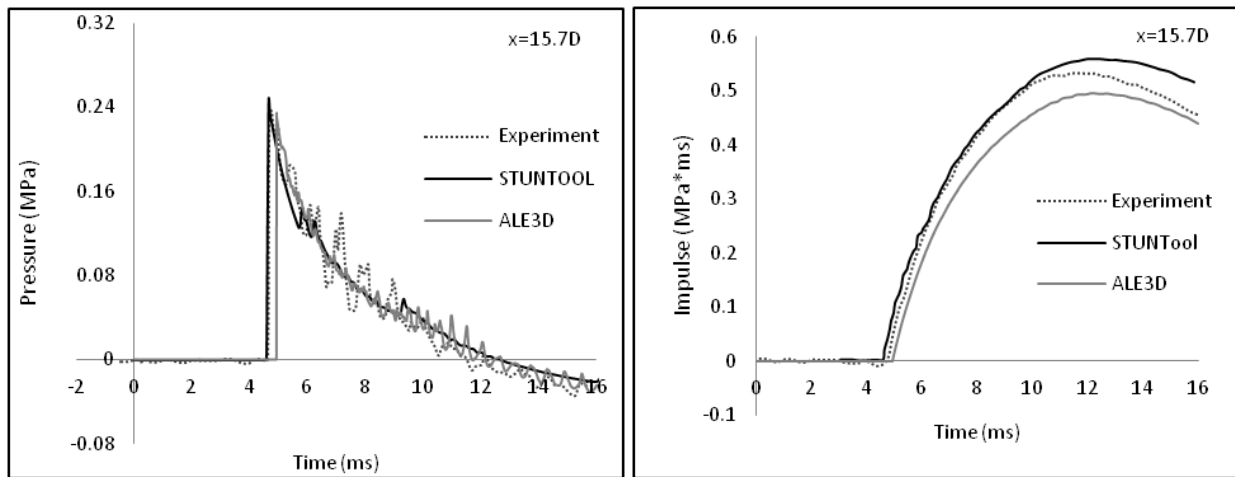Figure 1: Peak pressure and peak impulse results from the two simulations and the experiment [14].

Figure 2: Pressure (a) and impulse (b) profiles taken at 15.7D. Our STUNTOOL results show excellent agreement with the experiment.

MODEL VALIDATION: TWO PIPE EXPERIMENT

We also compare the performance of the two codes in modeling a blast in a more complex pipe system [16]. Here we compare the model results to data from an experiment involving an explosion in a tunnel where the blast wave encounters a sudden decrease in cross-section [17]. The experiment involved an explosive centered in a 1.8 meter long section of heavy duty steel pipe with an internal diameter of 14.6 cm (the detonation chamber). Connected to

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one side of the detonation chamber were four one-meter long segments of smooth Schedule 80 steel pipe with an internal diameter of 7.36 cm. On the other side, the same configuration was used except that the center two segments were replaced with grooved pipe in order to test the effects of wall roughness on the propagation of the blast wave. Pressure profiles were again obtained using diaphragm-type air blast gages flush-mounted to the wall of the pipe. No pressure gages were used in the detonation chamber. The charge was composition C-4 configured in a brick with a 5.04cm square cross-section. Three different charge weights were investigated. For the purpose of our validation, we compare to the smooth side only (assume a symmetry plane at the charge location) and a 340 gram charge in order to investigate the effect of the fourfold decrease in cross section that occurs at the end of the detonation chamber.

The experimental set up was again simulated assuming rigid walls with the STUN and ALE3D codes, and the ALE3D simulation was solved in 2D, using a cylindrical charge of with weight equal to that used in the experiment in order to employ axial symmetry. The STUN simulation again featured a spherical charge of the experimental weight. At this time our fast running STUNTOOL does not feature other charge geometries. The simulation details are given in Table 2. The computational time for the ALE3D simulation of this experiment is much less than the previous one because the symmetry at the charge location (x=0) results in a much smaller computational domain.

Table 2: Simulation details for comparison to small scale two pipe experiment

Simulation:	1D STUNTOOL	2D (ALE3D)
Resolution	6.4mm	2.0mm
# of Elements	773	50,000
Wall time	< 1 min	6.1 hours
Number of Processors	1	3
Total Computational Time	< 1 min	18.3 hours

Experimental measurements are not available in the detonation chamber; however, the numerical results from both codes show good agreement ten centimeters from the change in cross section (Figure 3). After the change in cross-section, the peak pressures obtained from the simulations are found to be significantly higher than experimental results (Figure 4). The agreement between the 2D result and the experiment improves with increasing distance down the tunnel (Figure 5), but STUNTOOL continues to report significantly higher pressure and impulse values.
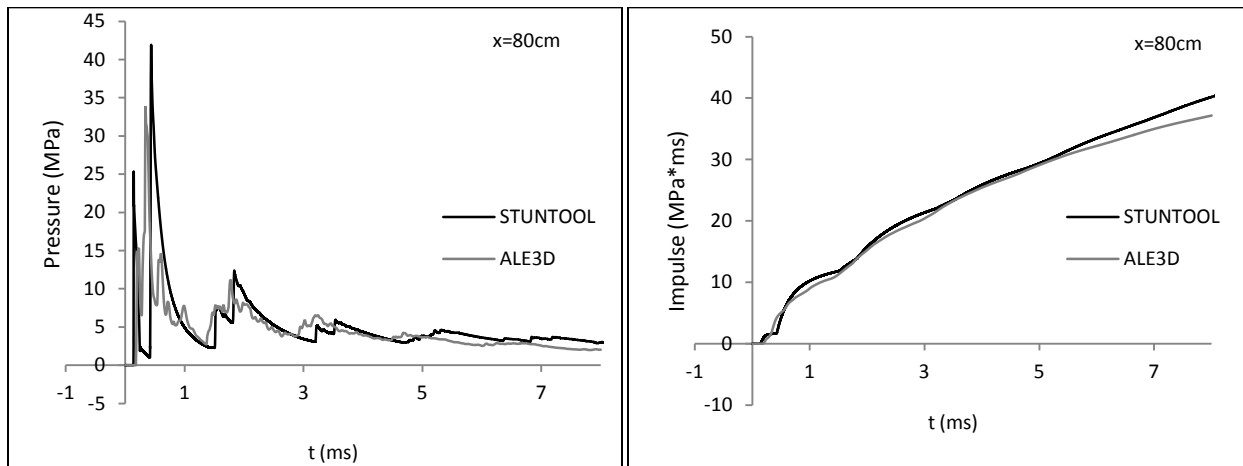

Figure 3: Pressure and impulse profiles for STUNTOOL and ALE3D calculations at a location within the blast chamber show good agreement.
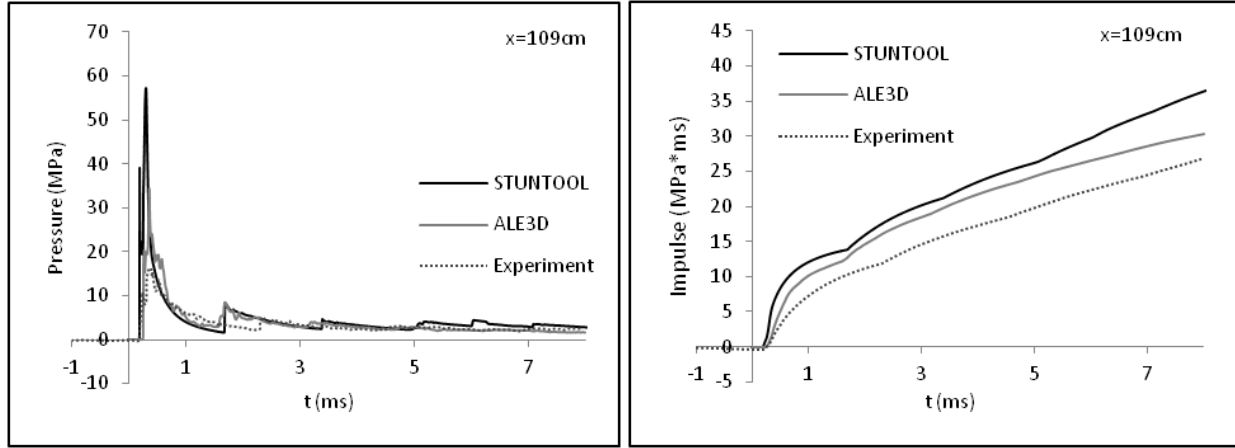
Figure 4: Pressure and impulse profiles for STUNTOOL, ALE3D and experimental results at a location just after the change in cross-section. Simulations over-predict the results compared to the experiment.
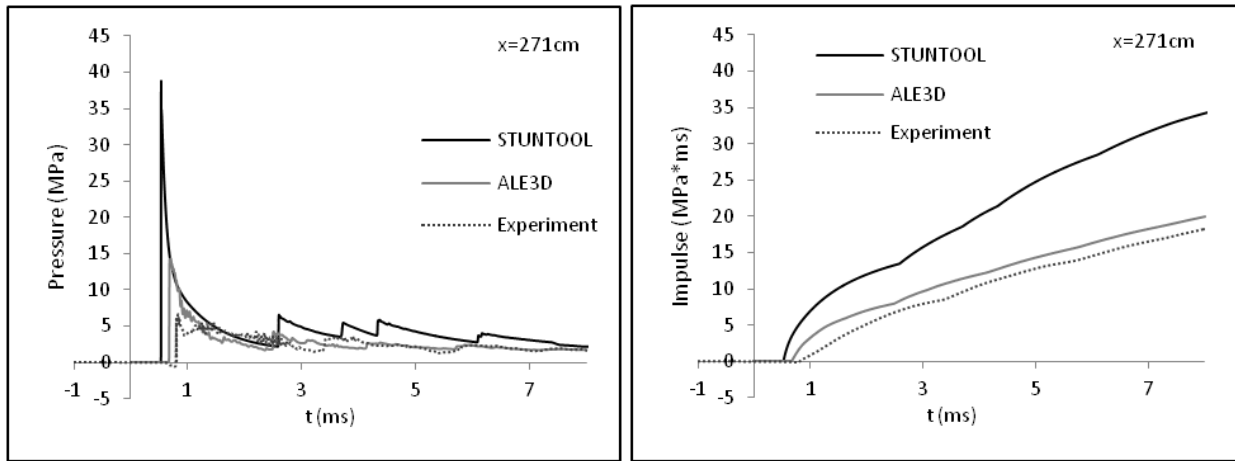

Figure 5: Pressure and impulse profiles for STUNTOOL, ALE3D and experimental results further down the tunnel from the change in cross-section, at x=271cm from the charge. ALE3D impulse begins to agree better with the experiment.

The peak pressure and impulse per unit area results obtained from STUN downstream of the interface are substantially higher than either the experimental or the ALE3D values. This discrepancy can be attributed to the time delay for the shock reflecting off the vertical rigid wall between the inner and outer tunnel radii to interact with the supersonic core flow into the decreased cross section. Figure 6 illustrates this effect through synthetic Schlieren pictures generated with ALE3D, each separated by 0.01ms. The leftmost picture shows a nearly normal shock approaching the pipe test section. The next picture shows an even stronger shock reflecting off the vertical end plate of the detonation chamber. The final image shows the reflected shock moving more or less spherically from the corner of the interface and beginning to interact with the core flow in the pipe test section. In the 1D case, the reflected and transmitted shocks are formed instantaneously across the entire cross section; no time delay is present. There can be no lateral variation in the 1D uniaxial flow, giving higher pressure values and increased shock speed downstream of the interface. Since the reflected shock pressure is much higher than behind the incident shock, the leading segment of the core flow is accelerated compared to both the 2D case and the experiment, causing the shorter arrival times and higher pressures observed in the results above. Moreover, the reflected shock in the detonation chamber will be stronger as it moves back towards the plane of detonation and reflects from there. The subsequent periodic spikes in pressure seen prominently in Figure 4 and Figure 5 are a direct result of these reflections and are responsible for the increasing discrepancy between the impulse results calculated with STUNTOOL and ALE3D (Figure 5).
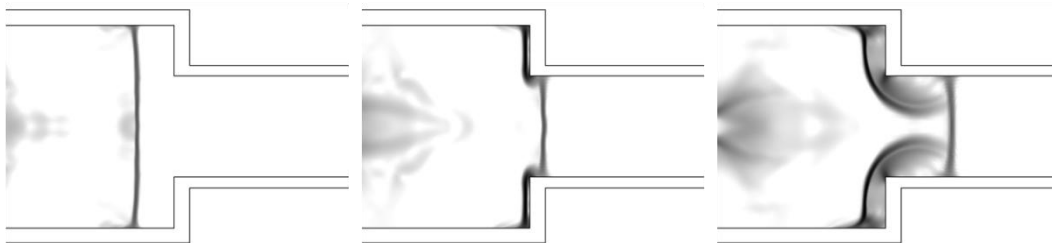
Figure 6: Synthetic Schlieren photograph of ALE3D simulation just prior to, during, and after blast wave enters tunnel test section.

CONCLUSIONS

A 1-1/2 dimensional physics tool for estimating blast effects in tunnels, STUNTOOL, and an axisymmetric code, ALE3D, are used to investigate the propagation of a blast wave through enclosed pipe systems and the results are compared to experimental results. STUN obtains results that match the experimental data exceptionally well when modeling a smooth, straight pipe. In the experiment involving a contraction in cross-sectional area, the numerical results from both codes are in good agreement before the change in area is encountered. Down tunnel from the contraction, STUN over-estimated peak pressure and impulse compared to both the experiment and the 2D simulation. Since the goal is to create a fast-running tool applicable for specific tunnel/station configurations, such an overestimate can provide an acceptable conservative bound for users mindful of this limitation of the code. More important is the gain in calculation efficiency, thus, the relative calculation times should be considered. The 1D calculation in each study was carried out on a single processor PC in less than a minute of clock time whereas the 2D calculations required 2300 hours (96 hours on 24 processors) for the single pipe and 18 hours (six hours of clock time with three processors) for the pipe with a contraction. The tendency for STUNTOOL to over-predict pressure and impulse from a blast wave that encounters an abrupt change in cross-section is a result of the lower dimensionality in the code necessary to produce a fast-running tool for problems of this nature. When the reduction in cross-sectional area is gradual, STUNTOOL performs more accurately [12]. We expect STUNTOOL to perform better for the converse case of a shock wave encountering a sudden increase in cross-section; ALE3D and STUNTOOL simulations are currently being conducted to investigate such a configuration.

ACKNOWLEDGEMENTS

REFERENCES

[1] Nichols, A. L. and the ALE3D team (2009). Users Manual for ALE3D, An Arbitrary Lagrange/Eulerian 2D and 3D Code System, Volume 2, Material and Chemical Models, Lawrence Livermore National Laboratory, UCRL-SM-404490.

[2] Lin, J. (2005). "DYNA3D: A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics User's Manual." UCRL-MA-107254.

[3] McGlaun, J.M., Thompson, M.G., and Elrick, M.G. (1990). "CTH: a three-dimensional shockwave physics code." *Int. J. Impact Eng,* Vol. 10: 351-360.

[4] Noble, C., Kokko, E., Darnell, I., Dunn, T., Haggler, L. and Leininger, L. (2005). "Concrete Model Descriptions and Summary of Benchmark Studies for Blast Effects Simulations," Lawrence Livermore National Laboratory, UCRL-TR-215024.

[5] McMichael, L.M., Noble, C., Margraf, J., and Glascoe, L. (2009). "Fully-Coupled Blast Effects Modeling of Large Critical Infrastructure." ASCE Fifth Congress on Forensic Engineering, November 10-15, LLNL-CONF-411649.

[6] Glascoe, L., Neuscamman, S., Lennox, K., Elmer, W., Glenn, L., McMichael, L. (2012). "A Fast-running Tool to Characterize Shock Damage on Enclosed Structures." Proceedings of the 2012 ASCE Structures Congress, LLNL-PROC-520618.

[7] Glascoe, L. L. McMichael, K.S. Vandersall, and J. Margraf. 2010. "Underwater blast experiments and mitigation for shock mitigation." Proceedings for the 14th International Detonation Symposium, Coeur D'Alene, Idaho, April 11-16, 2010 (LLNL-CONF-424235).

[8] William Elmer VII, Ertugrul Taciroglub, Larry McMichael, 2012. "Dynamic strength increase of plain concrete from high strain rate plasticity with shear dilation," *Int. J. Impact Eng*, v45:1-15.

[9] Lennox, K.P., and L. Glascoe. 2011. "Constrained classification for infrastructure threat assessment," Proceedings for the IEEE International Conference on Technologies for Homeland Security, 15-17 November, Waltham, MA.

[10] Glenn, L. A. (2001). "Simulating MARVEL with the STUN Code." Lawrence Livermore National Laboratory, UCRL-ID-143993 (June 6, 2001).

[11] Glenn, L. A. (1990). "Design limitations on ultra–high velocity projectile launchers." *Int. J. Impact Eng*, 10, 185.

[12] Glenn, L. A. (1997). "On how to make the fastest gun in the West." Proc. of the International Workshop on New Models and Numerical Codes for Shock Wave Processes in Condensed Media, St. Catherine's College, Oxford, U. K. (September 15-19 1997).

[13] Schlichting, H. (1979). *Boundary Layer Theory*, 7th ed., McGraw-Hill, New York

[14] Lunderman, C. and Ohrt, A. P. (1997). "Small-Scale Experiments of In-Tunnel Airblast from Internal and External Detonations." 8th International Symposium on Interactions of the Effects of Munitions with Structures, April 21-25, McLean, Virginia.

[15] Neuscamman, S., Glenn, L., Schebler, G., McMichael, L., and Glascoe, L. (2011) "Simulating Small-Scale Experiments of In-Tunnel Airblast Using STUN and ALE3D" Lawrence Livermore National Laboratory, LLNL-TR-498891.

[16] Glenn, L. A. and Neuscamman, S. J. (2011). "Computer simulation of blast waves in a tunnel with a sudden decrease in cross-section." Lawrence Livermore National Laboratory, LLNL-TR-496344

[17] Lunderman, C. V., Welch, C. R., Joachim, C. E., and Furey, J. S. (1993). "Effects of Tunnel Wall Roughness on Airblast from Internal Detonations – Results from Small-Scale Experiments." 64th Shock & Vibration Symposium, October 25-28, Fort Walton Beach, Florida.